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SELECTIONS ON HYDROGEOLOGY AND ENGINEERING GEOLOGY

- COMMUNIST CHINA -

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SELECTIONS ON HYDROGEOLOGY AND ENGINEERING GEOLOGY

- COMMUNIST CHINA -

[The following are translations of selected articles from Shui-wen Ti-chih Kung-ch'eng Ti-chih (Hydrogeology and Engineering Geology), Peiping, Number 6, 12 June 1960.]

CONTENTS

A RAPID METHOD OF ADJUSTING THE SCALES OF A HYDROMETER OF SOIL PARTICLE ANALYSIS

- Communist China -

/Following is the translation of an article by the Hsi-an Highway Academy, Testing and Research Laboratory, in Shui-wen Ti-chih Kung-ch'eng Ti-chih, 12 June 1960, pp. 29-30./

The method we will now describe is based on the Principle of Archimedes, which says that the weight of an hydrometer is equal to the weight of the liquid displaced by the hydrometer when it is submerged into a liquid. If we increase the density of the liquid, there will be a corresponding decrease in the submerged volume of the hydrometer placed in the liquid. This change is shown by the ups and downs of the glass bar of the hydrometer. Therefore, we may obtain the adjusting values of the scale of an hydrometer by studying the regularities in the volume changes of the hydrometer within its scale range.

I. Apparatus used.

1. Cylinder: Diameter = 6cm ± 1mm, Capacity = 1000cc.
2. Thermometer: 0~50°C, smallest reading 0.5°C.
3. Scale: 1/20mm (scales used by mechanics are accurate enough).
4. Others: Balance (sensitivity 1/1000 gr.), distilled water, coordinate sheet, etc.

II. Procedures of operation and formulae for calculation.

1. Measure the initial point L_0 of the scale of the hydrometer and the volume V below L_0. Also write down the adjusting value m' for the curved liquid surface.

Clean the hydrometer with distilled water and wipe it dry; weigh it to an accuracy of 1/1000/gr.; then put the hydrometer into the cylinder which contains 1000 cc. of distilled water of 20° ± 0.5°C (the room temperature is controlled

to about 20°C before putting the hydrometer into the water, so that there will not be too much temperature difference between the water and the hydrometer). Take a reading of the point of the hydrometer that meets the lower edge of the curved liquid surface; this reading is L_o (meanwhile, take a reading of the upper edge of the curved liquid surface and write down m', the adjusting value of the curved liquid surface). The volume of the part of the hydrometer below the initial point L_o can be found by using the following formula:

$$V = \frac{W}{\gamma_{w20}} \ (cm^3)$$

In which, w = the weight of the hydrometer (gr.)

γ_{w20} = the specific gravity of the distilled water at 20°C (0.998232)

2. Measure V_i, the volume between the initial point L_o and a certain point (in general, measure once for every 5 readings).

Take the hydrometer out of the distilled water, dry it with a handkerchief and measure with a scale the diameter corresponding to the initial point L_o. Then measure the diameters at certain points (in general, once for every 5 scales) and the distances d_i from L_o to these points. Finally calculate V_i, the volume between L_o and a certain point according to the following formula:

$$V_i = \frac{\pi}{4}\left(\frac{d + d_i}{2}\right)^2 L_i = 0.19635\,(d \quad d_i)^2 \ L_i$$

In which, d = the diameter at the initial point of the glass bar (cm).

d_i = the diameter corresponding to a certain point (cm).

L_i = the distance between L_o and that point (cm).

If the glass bar of the hydrometer has the same diameter throughout its length, then the formula becomes:

$$V_i = \frac{\pi}{4} d^2 L_i = 0.7854 d^2 L_i$$

3. Calculate the accurate scale that a hydrometer should have at a point .

The calculation formula for a 20°/20°C Type B hydrometer is as follows:

$$\Delta_{B20} = \frac{W}{(V - V_i)\gamma_{w20}}$$

In which, Δ_{B20} = the accurate scale that the 20°/20°C Type B hydrometer should have.

Other notations are the same as before.

For a $20^\circ/4^\circ C$ Type B hydrometer the formula is:

$$\Delta_{B4} = \frac{W}{V - V_i}$$

In which, Δ_{B4} = the accurate scale of a $20^\circ/4^\circ C$ Type B hydrometer.

For a Type A hydrometer the formula is:

$$R_A = \frac{(\Delta_{B20} - 1) \times 1000}{0.624413} = (\Delta_{B20} - 1) \times 1601.5051$$

In which, R_A = the accurate scale of a Type A hydrometer. Other notations are the same as before (see Ministry of Hydraulics: "The Specifications on the Operations of Soil Testing", p. 239).

4. The calculation of adjusting values.

The difference between the accurate scale a point should have and its direct reading is the adjusting value at that point. Because the correction value of the curved liquid surface is generally a constant, when we calculate the adjusting value for the scale, we may obtain H', the adjusting value for both the scale and the curved liquid surface.

For a $20^\circ/20^\circ C$ Type B hydrometer the formula is:

$$H' = \Delta_{B20} - (R_i - m')$$

In which, R = the direct reading of the point to be corrected.
m' = the adjusting value for the curved liquid surface of the hydrometer.
Others are the same as before.

For a $20^\circ/4^\circ C$ Type B hydrometer and Type A hydrometer, the calculating formuae are in the same form as the preceding one.

III. Example.

1. Number of the hydrometer: $20^\circ/20^\circ C$ B-1 (according to this laboratory).
2. Weight of the hydrometer: 86.843 gr.
3. Initial point reading L_0 (in distilled water, at $20^\circ C$, corresponding to the lower curved liquid surface) = 1.0013.
4. Volume under L_0:

$$V = \frac{86.843}{0.998232} = 86.9968 \ (cm^3)$$

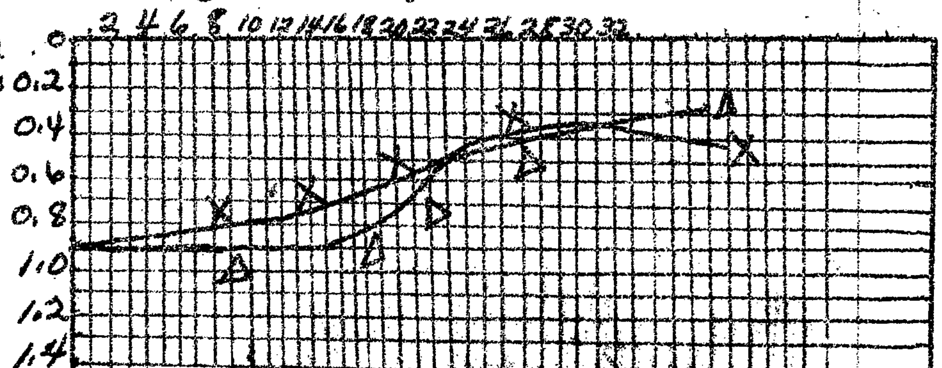
5. Other measured and calculated values are listed below:

(See next page)

Readings of point to be corrected. R_i	Diameter of glass bar at points to be corrected. d_i (cm)	Distances between initial point to the points to be corrected. L_i (cm)	Volumes between initial point to the points to be corrected. Y_i (cm)	Accurate readings calculated from formula Δ_{820}	Correcting values for scale and curved liquid surface $m' = \Delta_{820} - (R_i - m')$
1.0013	0.535	0	0	1.0000	-0.0009
1.0050	0.535	1.418	0.3188	1.0037	-0.0009
1.0100	0.535	3.320	0.7463	1.0087	-0.0009
1.0150	0.535	5.232	1.1762	1.0137	-0.0009
1.0200	0.535	7.188	1.6159	1.0189	-0.0007
1.0250	0.535	9.120	2.0502	1.0241	-0.0005
1.0300	0.535	10.982	2.4688	1.0292	-0.0004

Simplified readings of the hydrometer.

The simplified reading scales of hydrometer and the correcting value of the curved liquid surface.



The two curves in the graph show the comparison of results by two different methods. The Δ-curve corresponds to the rapid method and the x-curve to the standard solution method.

IV. Attentions to the operation.

1. Special care should be taken when measuring the diameters of the glass bar and the distances between points of the bar. From experience the measured values of dimeters tend to be higher than their true values.

2. In weighing the hydrometer and measuring its length, one has to be careful that the hydrometer and its glass bar will not be broken.

3. In measuring the distance L_i and the diameter d_2 of a certain scaled point, usually take readings every 5 scaled points. If some readings are questionable, measure some intermediate points.

4. If the scales can not be seen clearly by the naked eye when measuring, a low power magnifying glass (3-5) will be helpful.

The inaccuracy of the scales of hydrometers is one of the factors that causes errors during the procedure of analysing soil particles with an hydrometer. The radical solution of this problem is to improve and to unify the manufacture of hydrometers. The method introduced above is actually based upon the principle of hydrometer manufacturing. Take a 20°/20°C B-J hydrometer, for instance, and the forestated equation:

$$\Delta_{B20} = \frac{W}{(V - V_i)\gamma_{w20}}$$

In which $V_i = \frac{\pi}{4} d^2 L_i$. Substitution of the value of V_i into the equation one gets:

$$L_i = \frac{W}{\gamma_{w20}} \left(1 - \frac{1}{\Delta_{B20}}\right) \times 0.7854\, d^2$$

[Remarked by translator: This formula was misprinted; the right one should be:

$$L_i = \frac{W}{\gamma_{w20}} \left(1 - \frac{1}{\Delta_{B20}}\right) \div 0.7854\, d^2$$]

This is the method to calculate the distance from each point of the hydrometer to its initial point L_o. If we can control the weight w of the hydrometer, the diameter d of the glass bar and the distance L_i; if we can make all the scales accurately, according to their calculated values; and if we are able to adjust the initial point of the scale so that it will coincide with the actual initial point, then adjusting the scale is unnecessary. Furthermore, if we can place the zero point accurately on the top edge of the curved liquid surface at the initial point of the scale, the correction of the curved liquid surface can be omitted. It is very helpful in raising the quality and efficiency of our work to get rid of these corrections, especially the correction of the scales. We mention this as a suggestion to the manufacturers of hydrometers.

THE GENESIS OF THE PAI-LANG-KOU MINERAL SPRING OF KANSU AND RELATED PROBLEMS

- Communist China -

/Following is the translation of an article by Ts'ai Erh-fen (5591 1422 5358), Kansu Hydrogeological and Engineering Geological Group, in Shui-wen Ti-chih Kung-ch'eng Ti-chih, 12 June 1960, pp. 34-35./

I. Introduction.

The Pai-lang-kou mineral spring is located in the Ch'i-lien-shan area, has a linear distance of 23 km to the west of Su-nan Hsien and is on the left side of Pai-lang-kou (the upper course of the Li-yuan river).

The spring was found by a Russian geologist on his way to a geological survey party in the Ch'i-lien-shan area. It was identified as carbonated. Springs of such a nature are considered medically important, especially for the treatment of neurotic diseases and heart troubles. In view of this he suggested that a further investigation be made as the first step to a full development and usage of this mineral spring.

The mineral springs in the Ch'i-lien-shan folded zone have not been investigated. Springs of medical importance have never been mentioned in literature. The finding of this mineral spring, therefore, marks the beginning of an extensive investigation on such springs for their use in public health.

II. The geology and topography of the surrounding area.

The surrounding area is composed mostly of lower Paleozoic metamorphics. Silurian Lao-chun-shan conglomerate and some Carboniferous-Permian formations can be seen along Ko-pu-lang-kou. There are also Quaternary sediments (sand and gravel) covering the concave portions of the valley of Ko-pu-lang-kou.

1. The Yao-mo-shan System (Cambrian-Ordovician)

This system, developed along the Li-yuan river, consists of dark grey phyllites, light green hard sandstones, slates and schists. The associated thick igneous rocks are metamorphosed andesitic tuff, carbonatized andesitic tuff, metamorphosed quartz syenite and andesite. The exposed thickness is over 1000 m, while the total thickness of this system is 3000 m.

Fig. 1

2. Ch'uan-hsiung-kou Series (Lower Silurian)

This Series, exposed at the upper course of Ta-li-tung-kou, is composed chiefly of green, thick-bedded conglomerate with interbedded dark gray slate, phyllite and purplish sandy conglomerate. The conglomerates are cemented with siliceous material. The total thickness is 2800 m.

3. The Lao-chun-shan conglomerate (Upper Silurian)

This conglomerate is well developed along the lower course of the Pai-lang-kou. This formation, a typical product of molassic sedimentation, consists of purplish, massive conglomerate with siliceous cementing material. There are also some interbedded conglomeratic sandstones. In the valley of the Ta-li-tung-kou this conglomerate is in overthrust contact with the Yao-mo-shan system, thus providing a good access to the ascending mineral solution.

4. The Chou-liu-kou Series (Lower Carboniferous)

This Series, exposed over only a small area between the Tan-k'o-kou and the Ti-san-kou, has a thickness of about 150-200 m. It is composed mainly of dark grey limestone bearing fossil Yuan's corals and giant Productus. This series is overlain with disconformity by the Carboniferous-Permian strata.

5. Carboniferous-Permian System

This System, associated with the Lao-chun-shan conglomerate and the Chou-liu-kou Series, is composed of dark carbonic shale and muddy shale interbedded with dark grey,

thin limestones, sandstones and coal seams. The total thickness is about 250 m.

6. Quaternary

Quaternary covers the banks of the Li-yuan river valley. The lower part consists of conglomerate of the Chiu-chuan epoch, partially cemented by calcareous material; the upper part consists of recent, alluvial and projuvial sand and clay. The thickness varies from 2 to 3 meters. The mineral spring occurs in this formation.

The general trend of structure in the area under consideration is NW-SE. Let us take, as examples, a few major faults: The Ta-li-tung-kou overthrust strikes N 60°-70° W and dips to the northeast at an angle of 40°. The Yao-mo-shan system is overthrust upon the Lao-chun-shan conglomerate. The Tan-k'o-kou overthrust strikes N 50° W and dips 40°-50° SW. These two overthrusts are nearly parallel to each other. Therefore, the Li-yuan river valley is a graben.

The formation of mineral water is closely related to the joint system. The joints, well developed in the metamorphics of the lower Paleozoic, are generally of the shear and tension types.

The topography of this area shows an apparent dependence on the lithologic and structural features. The metamorphic rocks on the sides of the Li-yuan river valley form precipitous mountains standing up to a relative height of 500 m. The peaks are often covered with snow, which is a main source supplying the ground and superficial waters in this area.

Along the wide bottom of the Li-yuan river valley are subdued mountains. This is because the bottom was lowered relative to the overthrust sides and because the exposing Carboniferous-Permian strata are relatively soft.

III. A description of the mineral spring.

The Pai-lang-kou mineral spring is located on a terrace, composed of sand and clay and Chiu-chuan conglomerate, on the left side of the Pai-lang-kou and near its mouth. From Fig. 2 it can be seen that the mineral spring is right above the fault zone between the Yao-mo-shan system and the Lao-chun-shan conglomerate. The fault zone provides an ascending channel for the mineral water.

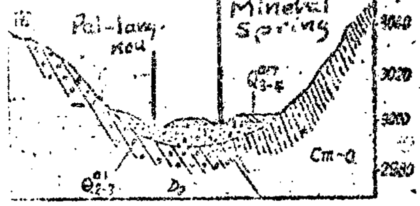


Fig. 2

The spring has a hole of diameter 4 m and depth of 2 m. The water enters the Pai-lang-kou and there forms a layer of rusty mud of possible medical importance on the surface over which it flows. There is also a thin layer of white stuff, possibly Na_2CO_3, around the hole, probably formed through the action of the escaping CO_2.

The mineral spring is transparent and light green. It contains an abundant amount of CO_2 and a mere sip makes you know it.

The temperature of the water is 5°C, indicating a source of shallow circulating water.

The measured flow is 0.18 liter per second or 15.6 tons per day.

Chemical analysis shows that the water contains sodium, calcium and magnesium bicarbonates with free CO_2, while the ground water and the river are of the calcium bicarbonate type, above 80% HCO_3. In addition to these three dominant positive ions the water contains a small amount of Li, Sr, B, Br and dissolvable SiO_2. The CO_2 content is 660 milligrams per liter; the pH value is 7.21; and the degree of mineralization is 2.8 grams per liter.

IV. The origin of the mineral spring.

According to the chemical analysis this mineral spring is classified under the first group in Alexadrov's Classification, i.e., of the Na-Ca-Mg Bicarbonate type. In addition its CO_2 content suggests a similarity to the (Narzan) mineral spring in Russia.

From the preceding statements this mineral solution may be considered to have formed through leaching. Rain and melting snow constitute the main source of water supply. Nothing can be said about the primary water of igneous origin. However, the formation of CO_2 in the mineral spring is related to igneous activities.

During the course of circulation of the mineral solution carbonates were dissolved and converted to bicarbonates, whereby the content of HCO_3^- increased. The amount of $SO_4^{=}$ also slightly increased (Shih 3).

Due to the presence of abundant HCO_3^- this circulating water possessed a strong dissolving power. Consequently, the amount of Na^+ and Mg^{++} continually increased, finally resulting with Na^+ predominant over Ca^{++}. This is because the hydrolysis of such minerals as albite:

$$2NaAlSi_3O_8 + 2CO_2 + 3H_2O \rightarrow H_4Al_2Si_2O_9 + 2Na^+ + 2HCO_3^- + 4SiO_2^+ \quad (1)$$

The increase in amount of Mg^{++} is undoubtedly due to the dissolving of $MgCO_3$ and magnesium silicates (as chlorite,

muscovite, hornblende, etc.) and the exchange of Ca^{++} in water with Mg^{++} in the surrounding rocks. For example:

$$CaMg(CO_3)_2 + Ca^{++} \rightarrow 2CaCO_3 + Mg^{++} \qquad (2)$$

The presence of rare elements such as Li^{+}, Sr^{++}, B^{+++}, etc, in the solution may also be ascribed to the hydrolysis of Li-mica, tourmaline, $SrSO_4$, etc. For instance:

$$SrSO_4 + 2NaHCO_3 \rightarrow Sr^{++} + CO_3^{--} + 2Na^{+} + SO_4^{---} + H_2O + CO_2 \qquad (3)$$

That there was an increase in the amount of SiO_2 and SO_4^{---} is also evident from Eqs. (1) and (3).

The three equations above give only an idealized picture of the reactions. The actual situation is far more complicated.

With the enrichment of Na, Ca, etc. the degree of mineralization gets higher and higher.

In short, running water was trapped in the fractures of bedrocks; in its descending course it caught more and more CO_2, making possible the enrichment and exchange of some elements.

Under the action of internal stress and hydraulic pressure the down-leaching solution finally found its way along the fault zone between the Lao-chun-shan conglomerate and the Yao-mo-shan system.

V. Conclusion.

Carbonated springs are not well known in this country. The spring under investigation is the first one found in Kansu Province. A further investigation of the origin of the spring is, therefore, significant both theoretically and practically.

From the above primary analysis, it is evident that the formation and distribution of the mineral spring is closely related to the old metamorphic rocks in this area.

From the Proterozoic Era down to the Silurian Period, igneous activities had been very active in the Ch'i-lien-shan geosyncline. Igneous rocks of great thickness can be seen at Te-jang-ta-pan, Chao-pi-shan, Yao-mo-shan, Ta-ye-kou, Su-yu-kou, along Pai-yang Ho, Pei-ta Ho, Hung-shui Ho, Li-yuan Ho and Nei Ho and also in the Nan-shan system and the Lao-chun-shan conglomerate. Thus, the deep-cut valleys and structurally active zones in these areas (including the Ta-li-tung-kou overthrust mentioned in this paper) are prospective places for finding new mineral springs. Because of the wide spread distribution of igneous rocks and strong disturbance of the earth's crust in the Ch'i-lien-shan folded zone,

various springs may be found there.

Since the mineral spring occurs in the Quaternary sediments of sand and gravel, it may have been diluted by the ground water in the valley of the Pai-lang-kou. It is, therefore, recommended that wells of considerable diameter be drilled through the Quaternary sediments to reach the "eye" of the spring, as shown in Fig. 3. This will render it possible to obtain fresh solutions and also to increase the amount of flow from the spring.

Fig. 3

THE REGULARITIES OF WATER SURFACE RECOVERY IN WELLS DRILLED IN FREE WATER AQUIFERS AND THEIR SIGNIFICANCE TO THE RAPID DETERMINATION OF WELL DISCHARGE AND COEFFICIENT OF PERMEABILITY.

- Communist China -

/Following is the translation of an article by Liang Chien-t'ang (4731 1696 2769), Group 8, Department of Geology, Yunan Province, in Shui-wen Ti-chih Kung-ch'eng Ti-chih, 12 June 1960, pp. 36-41./

I. Introduction.

The determination of the coefficient of permeability and well discharge in aquifers is one of the main purposes of engineering geological exploration. The methods used in the determination are usually the constant pumping test and the constant head test, both based on the Ch'iu Pu-i (5941 1580 5902) well theory /Translator note: In western countries, this theory is known as Thiem's theory./. These tests require a long observation time, as well as special and heavy equipment; hence, they are not economical. Furthermore, these tests and the Ch'iu Pu-i theory itself are but approximations. So it is the task of all workers in the field of geological hydrology to find a new testing method that will be more economical, more accurate, more reliable and more rapid. We must eliminate the remarkable shortcomings that exist in the above mentioned tests and make our work fulfill the requirements of socialistic reconstruction. The author analyzed the regularities in the change of water level in wells drilled in free water aquifers during water level recovery. Identified by some primary experiments, he is submitting a testing method different from those stated above. His is a method to determine the coefficient of permeability and well discharge by observing the regularities in the change

of water surface in the wells.

Russian scholars had already studied methods to determine the discharge in artesian aquifers and oil-bearing strata by analyzing the curves of pressure recovery in wells (drilled holes). They concluded that this kind of testing method had some remarkable drawbacks (1). The author has never read a discussion on the application to free water aquifers, so this paper can only be regarded as a trial. Any remarks on this paper will be appreciated.

II. The recovery movement of the water level in a well and the derivation of the differential equation of the movement.

After a period of water changing or pumping, the water level in a well drilled in free water aquifer will be higher or lower than the original underground water level. A radial water flow and a cone-shaped water level will be produced. If we stop charging or pumping, the water level in the well will then recover to its original static level. This kind of water level recovery movement is called simply water level recovery.

Take, for instance, the case of water drawdown after water changing stops. Suppose the well has a diameter 2r, the width of aquifer is H, and the top of the aquiclude is roughly level. When the charge stops, the water level in the well gradually drops due to continuous dispersion on radial water flow (Fig. 1): i.e.,

$$h_{01} \longrightarrow h_{02} \longrightarrow h_{03} \longrightarrow H$$

The corresponding conical water level also drops and disperses:

$$L_1 \longrightarrow L_2 \longrightarrow L_3 \longrightarrow \text{the cone vanishes}$$

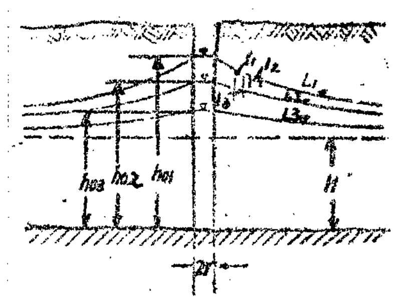


Fig. 1

It is obvious that in the whole process the total volume of radial water flow is equal to the volume of water

in the cone surrounded by the conical water surface and by the original water level. In a certain infinitesimal time interval dt, the conical surface drops down from a higher position to a lower one, and the amount of displaced water between these two levels equals the discharge of radial water flow in the time interval dt. If we analyze the radial flow by differentiation (Fig. 2), then in dt the change of water amount passing through two concentric cylinders with a radius difference dx is equal to the water discharge from the volume governed by the water surface gradient $\frac{\partial h}{\partial t}dt$ and the ring shaped cross-sectional area $2\pi x dx$ between the two cylinders. From this we can derive the differential equation for water flows of this type:

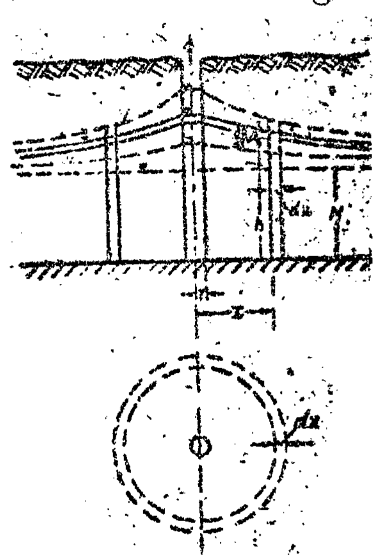


Fig. 2

$$\frac{\partial h}{\partial t} = \frac{K}{2\mu}\left(\frac{\partial^2 h^2}{\partial x^2} + \frac{1}{x}\frac{\partial h^2}{\partial x}\right) \qquad (1)$$

This is another form of "Pu-hsi-kung-su-ko"'s differential equation applied to well discharge problems. There are still difficulties in applying this equation to some practical cases. In the following sections we will discuss the regularities of this kind of movement under a relatively simple condition.

Generally speaking, at a certain time the water discharge of radial flow is higher in the outer cylindrical surface than in the inner one. The discharge passing through a cylindrical surface with radius x in time dt is equal to the sum of the water flowing out of the rocks and the water discharged from the well due to water surface dropping. This can be expressed simply as:

$$dz = \varphi(x, t) + \pi r_0^2 \frac{dh_0}{dt} dt$$

in which $\varphi(x, t)$ represents the amount of water flowing out of the rocks in the cylinder in time dt when the water level drops. Because the discharge water notonly is the water discharged between the two water surfaces corresponding to time difference dt, but also contains some residual water flow from above the original water surface, we can not calculate simply the volume of the rock and express the water discharged from it by simply the product of the volume on the rock and its coefficient of water supply. We express the

amount of water flowing out of the rocks by a function $\varphi(x,t)$.
The above equation can be written as:

$$Q = -\frac{ds}{dt} = -\frac{\varphi(x,t)}{dt} - \pi r^2 \frac{dh_0}{dt} \qquad (2)$$

Based on Darcy's Law:

$$Q = -K 2\pi x h \frac{dh}{dx} \qquad (3)$$

In equation (3) the water head gradient $\frac{dh}{dx}$ correspondint to a certain flow line is theoretically the ratio of differentials of the water head and the flow line itself, i.e.,

$$I = \frac{-dh}{dl} = \sin\theta$$

When the slope of the flow line is small, the difference between $\sin\theta$ and $\tan\theta$ is insignificant. In well discharge problems the mean I-value of the flow lines at points located on a vertical line is not $\sin\theta$. So we usually use $\tan\theta$ as the mean water head gradient of the points lying on a vertical line, i.e.,

$$I = \frac{dh}{dx} = \tan\theta$$

In the radial water flow movement, the I-value varies with t and x, as shown in Fig. 1. This means that at the same time x, I_1 of one point differs from I_2 of another point, and, similarly, that at the same point, I_1 corresponding to a certain time differs from I_3 corresponding to a different time. In the following we will discuss the variation of I-values on vertical lines with the same x when the water surface drops.

Assume that near the wall of the well there are two vertical lines h_1 and h_2, one unit length apart from each other, in the profile chart (fig. 3).
Here:

$$I = \frac{h_1 - h_2}{1} = h_1 - h_2$$

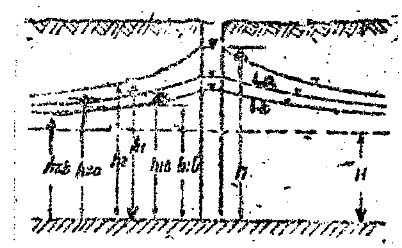


Fig. 3

The water surface lines and the water level in the well drop to their static positions after a certain time period. The drawdown of the water surface line at vertical h_1 is greater than that at h_2 ($h_1 > h_2$) because of the continuity of the water level drawdown. We also know that at any short time interval the drawdown at h_1 is greater than that at h_2, i.e.,

$$h_{1a} - h_{1b} > h_{2a} - h_{2b}$$

and:

$$(h_{1a} - h_{1b}) - (h_{2a} - h_{2b}) = \Delta I$$

(Notice that the distance between h_1 and h_2 is unity)
ΔI is the variation of the I-value when the water surface line drops from L_a to L_b. The process of the water surface line drawdown may be considered to be the combination of many small drawdowns $h_a - h_b$, the sum of the small drawdowns is h-H, and the sum of their corresponding ΔI is I. If we let the small drawdowns have definite lengths, then the number of drawdown intervals will decrease as the value of h-H becomes smaller due to water surface dropping. The sum of ΔI will also become smaller as the number of drawdown intervals decreases.

The forestated analysis is based on the assumption that $I = \tan\theta$, the result being the same if we let I be $\sin\theta$. This result can be simply stated: As the water surface line drops, the absolute value of the water head gradient on verticals with the same x becomes smaller as the absolute value of h-H decreases.

This analysis does not show the relationship between h-H and I. Here we assume they have an approximate linear relationship in some simple cases, i.e.,

$$I = \frac{dh}{dx} = -\lambda(h-H) \tag{4}$$

in which λ is a coefficient.

The author points out again that the relationship mentioned above is true only for verticals having the same x. We must not think that there is a coefficient λ throughout the radial water flow. At verticals having different x, the λ values are different. When the water surface drops, h-H is positive and $\frac{dh}{dx}$, negative, so that the negative sign appears on the right side of equation (4).

From equations (3) and (4) we know that on a cylindrical surface with radius x:

$$Q = K 2\pi x h \lambda (h-H) \tag{5}$$

When the surface of the cylinder coincides with the wall of the well, then $x = r$, $h = h_o$, $\lambda = \lambda_o$ and in equation (2) $\frac{\varphi(x \cdot t)}{dt} = 0$. Hence, equation (2) becomes:

$$Q = -\pi r^2 \frac{dh_o}{dt} \tag{6}$$

Equation (5) becomes:

$$Q = K 2\pi r \lambda_o h_o (h_o - H) \tag{7}$$

Comparing (6) and (7):

$$2K\lambda_o h_o (h_o - H) = -r \frac{dh_o}{dt} \tag{8}$$

Separating the variables and integrating equation (8):

$$\int dt = \frac{-r}{2K\lambda_o} \cdot \int \frac{dh_o}{h_o(h_o - H)} + C_1$$

$$\left.\begin{aligned} t &= \frac{-r}{2K\lambda_0 H}\cdot\log_e\frac{h_0-H}{h_0}+C_1 \\ \text{or:}\quad h_0 &= \frac{H}{1-Ce^{\frac{-2K\lambda_0 H}{r}t}} \end{aligned}\right\}\quad(9)$$

This is a simple formula showing the regularity of the well water surface recovery in the drawdown process. The boundary conditions of this equation are at t=0, $h_0=\frac{H}{1-C}$, $C=\frac{h_0-H}{h_0}$.

This is the water surface in the well when the drawdown starts.

If we pump water from the well, the water surface will have an upward recovery after the pumping stops. When S is small, a regularity similar to equation (9) can be obtained. Corresponding to equation (6):

$$Q=\pi r^2\frac{dh_0}{dt}\qquad(10)$$

Equation (7) becomes:

$$\begin{aligned} Q &= -\lambda_0(h_0-H)h_0 2\pi K r = \\ &= \lambda_0(H-h_0)h_0 2\pi K r \end{aligned}\qquad(11)$$

Comparing the two equations:

$$2K\lambda_0 h_0(H-h_0)=r\frac{dh_0}{dt}$$

Separating and integrating:

$$\left.\begin{aligned} t &= \frac{-r}{2K\lambda_0 H}\cdot\log_e\frac{H-h_0}{h_0}+C_1 \\ \text{or:}\quad h_0 &= \frac{H}{1+Ce^{\frac{-2K\lambda_0 H}{r}t}} \end{aligned}\right\}\qquad(12)$$

It is clear that equation (9) differs from equation (12) only in the sign of the term $Ce^{\frac{-2K\lambda_0 H}{r}t}$. The latter has meaning only if: $H-h_0=S<H$

t	h_0	h_0-H	$\varepsilon=-\log_e\frac{h_0-H}{h_0}$	r	H
6	97.70	66.17	0.3599	110	29.53
8	63.82	63.79	0.3304	"	29.53
9	62.07	62.54	0.3868	"	29.53
26	68.34	38.71	0.5634	"	29.53
28	66.53	37.02	0.5865	"	29.53
31	64.04	34.51	0.6 83	"	29.53
75	44.03	14.50	1.1107	"	29.53
185	32.65	3.12	2.3458	"	29.53

Table 11

III. The practical verification of the regularities of well water surface recovery.

The author observed three wells and found that the results of the observations coincide with the forestated regularities. Here we take these results as examples showing how they agree with our theory.

Before stating the example, let us look at equation (9):

$$t = \frac{-r}{2K\lambda_0 H} \log_e \frac{h_0 - H}{h_0} + C_1 \qquad (9)$$

in which $\frac{r}{2K\lambda_0 H}$ is a constant. It is clear that $\log_e \frac{h_0 - H}{h_0}$ varies linearly with t. In the process of the water surface drawdown, we measure the water level at different times and calculate the values of $\log \frac{h_0 - H}{h_0}$. Then we plot these values against their corresponding time in a rectangular coordinate system. If they agree with the regularity in equation (9), the plotted curve must be a straight line.

The bedrock into which we drilled the wells was composed of medium and fine grained quartzite with low permeability and contained some tiny cracks. The impervious bottom was shale with a small angle of inclination.

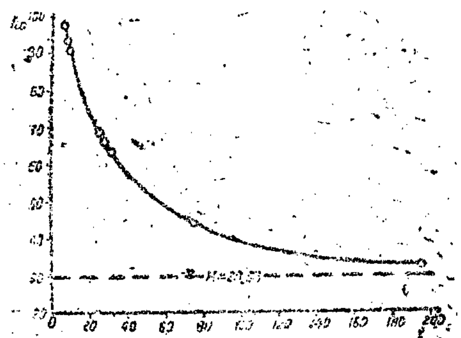


Fig. (4a)

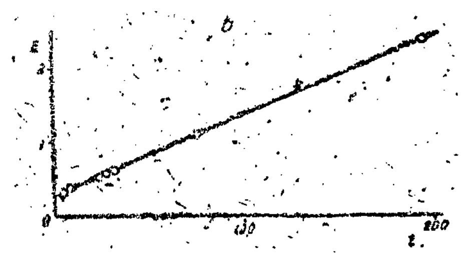


Fig. (4b)

Testing well No. 1: The observed data of the drawdown after water charging was stopped are tabulated in Table (1) (on preceding page). h_0 is plotted against t in Fig. (4a). If we plot $-\log_e \frac{h_0 - H}{h_0}$ values instead of the h 's along the abscissa, we will get a straight line, as shown in Fig. (4b).

t	h_0	$h_0 - H$	$E = -\log_e \frac{h_0 - H}{h_0}$	r	H
0	61.65	4.65	2.6005	130	58.0
2	61.74	3.74	2.8039	130	58.0
4	61.11	3.11	2.9779	130	58.0
7	60.38	2.38	3.2338	130	58.0
13	59.50	1.60	3.6907	89	58.0
20	59.03	1.03	4.0487	89	58.0
30	58.61	0.61	4.5654	89	58.0
40	58.36	0.36	5.0883	89	58.0
45	58.265	0.265	5.3924	89	58.0

Table 2

Fig. (5a)

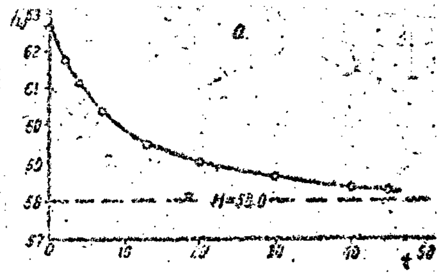
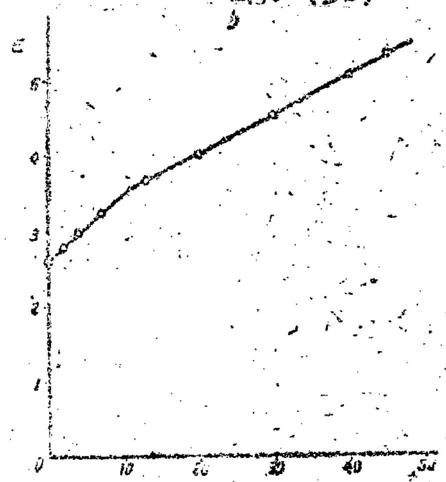


Fig. (5b)



Testing well No. 2: The observed data are tabulated in Table (2), and the t vs h_e and t vs $-\log_e \frac{h_e - H}{h_o}$ curves are plotted in Figures (5a) and (5b), respectively. What interests us most is that as the water surface dropped to the point where the diameter of the well changed (from 130 mm to 89mm), we find that in Fig. (5b) a corresponding turning point and two straight lines with different slopes are formed. The reason is quite simple and clear; as the well diameter changes, there is no change in the linear relationship of h_e and $-\log_e \frac{h_e - H}{h_o}$, but the slope $\frac{r}{2K\lambda_o H}$ of the straight line no longer remains the same. We know that the values K, H, and λ_o are independent of the well's diameter, so that the value $a = \frac{r}{2K\lambda_o H}$ varies proportionally as r changes. As we see in Fig. (5b), a (the slope) is greater before the change of the diameter (2r=130mm) and smaller after the change (2r=89mm). This is very strong support to the regularities stated above.

Testing well No. 3: The observed data also coincide with our theory (Omitted).

IV. The determination of the well's discharge and the coefficient of permeability by measuring the regularities of the water surface recovery.

1. The determination the the well's discharge. As stated in the previous section, by observing the water level at different times in the process of water surface drawdown, we are able to plot a graph according to equation (9). The values $\frac{r}{2K\lambda_o H}$ and C_1 are found from the graph (*1) or by the

(*1) In finding C_1 and E, good results can not be obtained if the S value is very small. Because H values vary with many factors in natural conditions, different values are found at different times. When S is large, the drawdown is due mainly to the head pressue of S, and the influence of all the other factors become relatively negligible. When S is small, the water level approaches H and the influence from other factors are of the same order as S; hence, can not be neglected.

following formulae:

$$\left.\begin{aligned} a\sum^{n} E^2 + C_1\sum^{n} E - \sum^{n} Et = 0 \\ a\sum^{n} E + nC_1 - \sum^{n} t = 0 \end{aligned}\right\} \qquad (13)$$

in which,

$$a = \frac{r}{2K\lambda_0 H}, \quad E = -\log_e \frac{h_0 - H}{h_0}.$$

Thus, the relation formulae of h_0-t together with their related coefficients C and a_e are determined:

$$h_0 = \frac{H}{1 - Ce^{-at}} \qquad (14)$$

In equation (6) the well discharge Q is the product of πr^2 and the differentiation of h_0 with respect to t. The differentiation of h_0 is :

$$\frac{dh_0}{dt} = \frac{-HaC_e^{-at}}{(1 - Ce^{-at})^2} \qquad (15)$$

By using equations (6), (14) and (15) we can calculate Q values corresponding to any h_0. We know that the only thing we have to do to determine the well discharge is investigate the variation of the water level drawdown. This method is obviously the most economical and the fastest one we have ever had, for it needs no heavy mechanical instruments. In cases where the underground water surface is very deep, this method is especially significant (in this case pumping is very inconvenient and constant charging to the well is also difficult). In aquifers with low permeability we may observe the drawdown of the water used for washing the well, right after the driller is taken off without having to pour water into the well. Two of the wells in our example were observed in that way. When aquifers are more permeable, the water level drops fast after charging stops. In order to have an accurat observation, the author suggests the following simple method:

Use an instrument as shown in Fig. (6). A is the main switch and by turning it we are able to connect it to switches 1, 2, 3, etc. The ends of the metal wires connected to these switches are located on different levels of the well. First, onnect A to 1. The light in the indicator will be nn before the water level drops

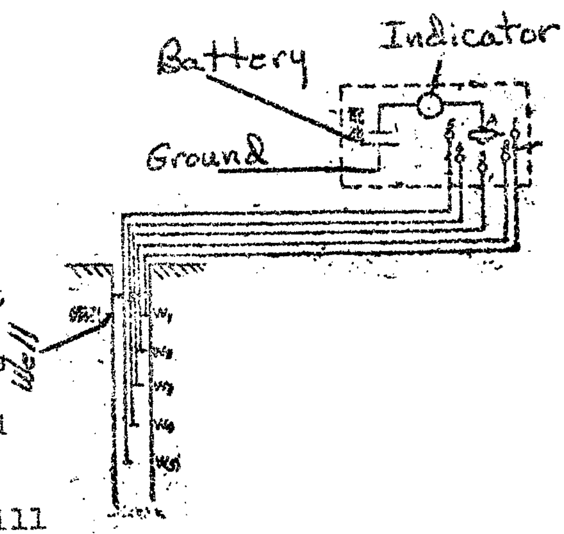


Fig. 6

to W_1 since the circuit is closed. Record the time that the light is off, giving the time corresponding to drawdown W_1. Similarly connect A to 2, 3, etc., getting W_2, W_3, etc., respectively.

2. Calculation of the coefficient of permeability. In equation (9):

$$a = \frac{r}{2K\lambda_0 H}$$

$$\therefore \quad K = \frac{r}{2\lambda_0 H a}$$

Therefore, in calculation K values by equation (9), λ_0 has to be known. Before trying to determine λ_0, the author thinks that if Q values measured by the outlined method agree with the true Q values (that is to say, if the method is proved to have general significance); also, if Q values determined by Chiu Pu-i constant head test are close to the true ones; then we can substitute the values of Q and the related coefficients found in our test into Chiu Pu-i's formula, together with other equations containing R and K, and hence, find the coefficient of permeability.

It should be pointed out that the method and equation (9) in this paper are derived from the regularities of drawdown h_0, while Chiu Pu-i's formula is based on the assumption that h_0, Q and R are nearly stable, although the stable condition actually does not exist. Therefore, the meanings of these two approaches are different, even though they might have very close results. Here we can compare the results and see how close they would be.

Comparing equation (7) and Chiu Pu-i Formula:

$$Q = \frac{\pi K}{\log_e \frac{R}{r}}(h_0 - H)(h_0 + H) \tag{16}$$

This gives:

$$2r\lambda_0 = \frac{1 + \frac{H}{h_0}}{\log_e \frac{R}{r}} \tag{17}$$

The numerator on the right-hand side of equation (17), $1 + \frac{H}{h_0} = 1 + \frac{H}{H+S}$.

When S changes from 0 to ∞, the corresponding change of $1 + \frac{H}{h_0}$ lies between 2 and 1. In general, the practical range of Chiu Pu-i's Formula is $S < \frac{H}{2}$, and the corresponding change of $1 + \frac{H}{h_0}$ lies between 1.66 and 2.

The denominator $\log_e \frac{R}{r}$ on the right side of equation (17) increases slowly, whether the h_0 value increases, decreases or remains unchanged. This is because of the constant divergence of the radial water flow and the conical water surface. The value $\log_e \frac{R}{r}$ changes only slightly as

R becomes larger. If, for example, R becomes 10R, then:

$$\log_{10}\frac{10R}{r} = 1 + \log_{10}\frac{R}{r}$$

$$\log_{10}\frac{10R}{r} - \log_{10}\frac{R}{r} = 1$$

That is to say that the increment $\log_e \frac{R}{r}$ is only 1 as **R** becomes 10x larger. In practical cases R never changes that much; it increases slowly, causing the increment of the denominator $\log_e \frac{R}{r}$ to be very small.

Now take a look at the right side of equation (17). The numerator increases slowly within the range of 1.66 to 2.0, while the denominator also increases, though more slowly than the numerator, so that the quotient remains nearly unchanged. This agrees with the assumption that λ_o on the left-hand side of equation (17) is a constant.

V. The regularity of well water surface recovery as appearing in an aquifer that does not contain water.

In case the aquifer contains no water: H=0 and $h_o - H = h_o = S$. Then equation (7) becomes:

$$Q = K 2\pi r \lambda_0 h_0^2 \qquad (18)$$

Comparison of equation (6) and (18) gives:

$$-r \cdot \frac{dh_0}{dt} = K 2 \lambda_0 h_0^2 \qquad (19)$$

Separating and integrating: $\int dt = \frac{-r}{2K\lambda_0} \cdot \int \frac{dh_0}{h_0^2} + C_1$

$$t = \frac{r}{2K\lambda_0} \cdot \frac{1}{h_0} + C_1 \qquad (20)$$

or: $$h_0 = \frac{r}{2K\lambda_0} \cdot \frac{1}{t - C_1}$$

Here we get the reverse proportionality of h_o and t in well recovery in an aquifer containing no water.

Taking t=0 gives: $C = -\frac{r}{2K\lambda_o h_o}$

Taking the logarithm of both sides of equation (20) yields:

$$\log_e h_o = -\log_e (t - C_1) + \log_e \frac{r}{2K\lambda_o} \qquad (21)$$

in which $\log_e \frac{r}{2K\lambda_o}$ is a constant. Hence, $\log_e h_o$ varies linearly with $\log_e (t - C_1)$. If we plot the h_o and $t - C_1$ values on a logarithm scale, we will get a straight line with -1 as its slope, corresponding to equation (21).

In measuring discharge Q, the method is similar to that in the previous section.

Through the discussion of sections IV and V, we know that the recovery of water surface drawdown has some particular features when the aquifer contains water and has

others when the aquifer does not. This gives us a method to distinguish the two different hydrogeological characteristics of bedrocks. It is well known that in some stratum whose boundary with aquiclude is not clear, it is difficult to discover whether or not the aquifer contains water, because there exists and artificial water level in the well caused by constant charging of the water from the washing during well drilling. Now we may distinguish between them by their features shown in the drawdown. We only need observe the variations of drawdowns and analyze the data, and if they agree with the regularities of equations (20) and (21), we know the aquifer contains no water; if they agree with equation (9), then the aquifer should contain water.

VI. Conclusions.

1. In a free water aquifer, the recovery of well water surface follows the movement of radial water flow. In the process of water drawdown, in time interval dt, the amount of water passing the cylindrical surface of radius x is the sum of the displace water in the rocks and the water flowing out the well. When the water surface drops, the absolute value of the water gradient on the verticals, corresponding to a certain x, decreases as the value of h-H decreases. Based on these fundamental theorems, the author derived a formula showing the regularity of water surface recovery in wells during the drawdown:

$$h_0 = \frac{H}{1 - Ce^{\frac{-2K\lambda_0 H}{r}t}} \tag{9}$$

This regularity has been proved by some preliminary experiments. Basing the following on this regularity, we find the fastest and the most economical method for the determination of well discharge and the value of K. This method is especially significant when using aquifers where the water level is deep and the soil is less permeable.

2. By using the same principles as above, a formula is derived for the case of a small S showing the regularity of water surface recovery after pumping stops (water surface rises):

$$h_0 = \frac{H}{1 + Ce^{\frac{-2K\lambda_0 H}{r}t}} \tag{12}$$

In aquifers not containing water, the formula of regularity is:

$$h_0 = \frac{r}{2K\lambda_0} \cdot \frac{1}{t - C_1} \tag{20}$$

The difference of regularity appearing in aquifers having different hydrogeological features gives us a simple way to distinguich the aquifers which contain water from those that do not.

3. If the regularities discussed in this paper can be proved, no doubt, the tedious hydrogeological and engineering geological experimental works in the field can be simplified and speeded to a great extent. We suggest that other departments in our field also make some efforts in researching into this problem.

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